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PRELIMINARY CORNEAL DAMAGE THRESHOLD STUDIES WITH HF-DF CHEMICAL LASERS

Donald J. Spencer, et al

Aerospace Corporation

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Preliminary Corneal Damage Threshold Studies with HF-DF Chemical Lasers

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Laboratory Operations
THE AEROSPACE CORPORATION

Prepared for SPACE AND MISSILE SYSTEMS ORGANIZATION
AIR FORCE SYSTEMS COMMAND
LOS ANGELES AIR FORCE STATION
Los Angeles, California

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FOREWORD

This report is published by The Aerospace Corporation, El Segundo, California. It reflects research supported by the Department of Defense through the Air Force Space and Missile Systems Organization under Contract No. F04701-73-C-0074.

This report, which documents research carried out in February and March 1972, was submitted on 20 March 1973 to 1st Lt Ernest L. Lockwood, DYAE, for review and approval.

Contributors to this study included Donald J. Spencer, Henry A. Bixler, Mark E. Gerard, Samuel V. Moore, Harold Mirels, Martin Lundquist, Pierre Valenzuela, and James S. Whittier, The Aerospace Corporation; Major Irving L. Dunsky, Captain David Egbert, Lieutenant Peter Laudieri, Staff Sergeant Carrol Houser, and Technical Sergeant Ralph Keller, U.S.A.F. School of Aerospace Medicine; Major R. Bruce Bedell, James L. Helfrich, Bruce Stuck, and Eugene Carpino, Army Medical Research and Development Command/Army Material Command Joint Laser Safety Team, Frankford Arsenal; and Captain Curtis D. Williams, Space and Missile Systems Organization.

Approved

W. R. Warren, Jr., Director
Aerodynamics and Propulsion
Research Laboratory

Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

George P. Field for
Ernest L. Lockwood, 1st Lt, USAF
Project Officer

ABSTRACT

A series of biomedical experiments was performed in The Aerospace Corporation HF/DF chemical lasers under direction of the USAF School of Aerospace Medicine (SAM), Aerospace Medical Division (AMD), to establish laser safety criteria. Minimal threshold levels for visual corneal damage to the rhesus monkey eye due to exposure to HF and DF wavelengths (~2.8 and ~3.7 μm, respectively) were determined for exposure times of 10^{-7}, 10^{-2}, 2.5×10^{-2}, 10^{-1}, and 5×10^{-1} sec duration. The DF laser damage threshold energies are 3 times higher than the HF laser damage thresholds for all conditions tested. HF laser damage thresholds range from ~1 mJ over a 1-mm-diam circular area at 10^{-7} sec exposure time to ~50 mJ at 0.5 sec exposure time. The data contained in this report are preliminary and tentative only. A statistical analysis, currently under way at SAM, will result in the release of a definitive report in the near future. The purpose of this report is to document test activities, procedures, and conditions and to provide guidance in outlining anticipated future testing requirements.

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FIGURES

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I. INTRODUCTION

A series of biomedical experiments using chemical lasers was performed in the Aerodynamics and Propulsion Research Laboratory under the direction of personnel from the USAF School of Aerospace Medicine (SAM), Aerospace Medical Division (AMD), Brooks Air Force Base, Texas. The purpose of the tests was to establish safety criteria for Air Force-operated laser systems in the 2.6- to 4-μm wavelength range. Threshold damage levels were determined for minimal visual corneal damage to the rhesus monkey eye from radiation emanating from HF and DF chemical lasers operating in both continuous and pulsed modes. These are the first corneal damage threshold data obtained at these wavelengths.

This test series constituted a field trip by the SAM personnel and covered the time period from 7 February through 30 March 1972. Approximately 140 rhesus monkeys were air-transported to the test site during the 2-month period and were housed in individual cages in an air-conditioned trailer especially prepared for animal handling. Approximately 50 monkeys were housed in the trailer at once, and the animals were rotated back to Brooks AFB upon the arrival of replacements. A team of specialists from Frankford Arsenal, Philadelphia, Pa., was also present during certain stages of the experiments to aid in laser beam calibration and lesion confirmation in the test animals. The entire field trip effort was under the direction of Major. I. Dunsky of SAM, who will prepare a report of this program and the final experimental results as a SAM publication. The purpose of the present report is to document the test activities, procedures, and conditions. Interim threshold damage values are also included for guidance in outlining future test requirements, but these data have not undergone statistical analysis and should be considered tentative and indicative, rather than absolute.

II. EXPERIMENTAL ARRAY

The principal testing effort involved the use of a continuous chemical laser with a precise, repeatable shutter assembly that controlled exposure times. The HF/DF continuous chemical laser employed in the test series is located in Building 130, Los Angeles Air Force Station, Room 30 and is designated SDL-30 (Supersonic Diffusion Laser - Room 30). Performance details of this type of laser may be found in Refs. 1 and 2. The operational parameters of interest are tabulated in the Appendix. Laser power was coupled out of an apertured (3-mm-diam) silicon flat and was transmitted along the optical path shown in Figure 1. The grating (B&L 300 1/mm blazed at 2.5 μm) was used at near autocollimation for single line testing and was replaced with an optical flat for multiline operation.

The laser exit beam is located 41 in. above floor level. Use of mirror assembly M_1, consisting of two flats, raises the beam 5 in. and turns its direction of propagation 90 deg. Mirror assembly M_1 raises the beam to 46 in. so as to make the beam level with the point of focus F. Mirror M_2, with a 120-in. radius of curvature, converges the beam to the focus F. The cornea of the subject's eye is placed at the point F.

Temporal and spatial beam scans were made at the focus to determine the extent of power modulation about the average power levels and to determine the beam shape for heat flux calculations. Beam power modulation at 360 cps, the rectifier power supply ripple frequency, was present during initial calibration tests, but improved arc operation resulted in the minimal ripple signal of Figure 2a. The spatial scan showed the beam to be Gaussian in shape with a ~1-mm diameter at the 1/e waist for a properly tuned cavity; see Figure 2b. Spatial scans were made at each test setting. The duration of transmission of the beam to F was controlled by a precisely timed shutter assembly, shown in Figure 1. The beam was deflected to a power meter P when the shutter was closed. Nominal flux conditions were assured by measurement of average power immediately prior to and immediately after

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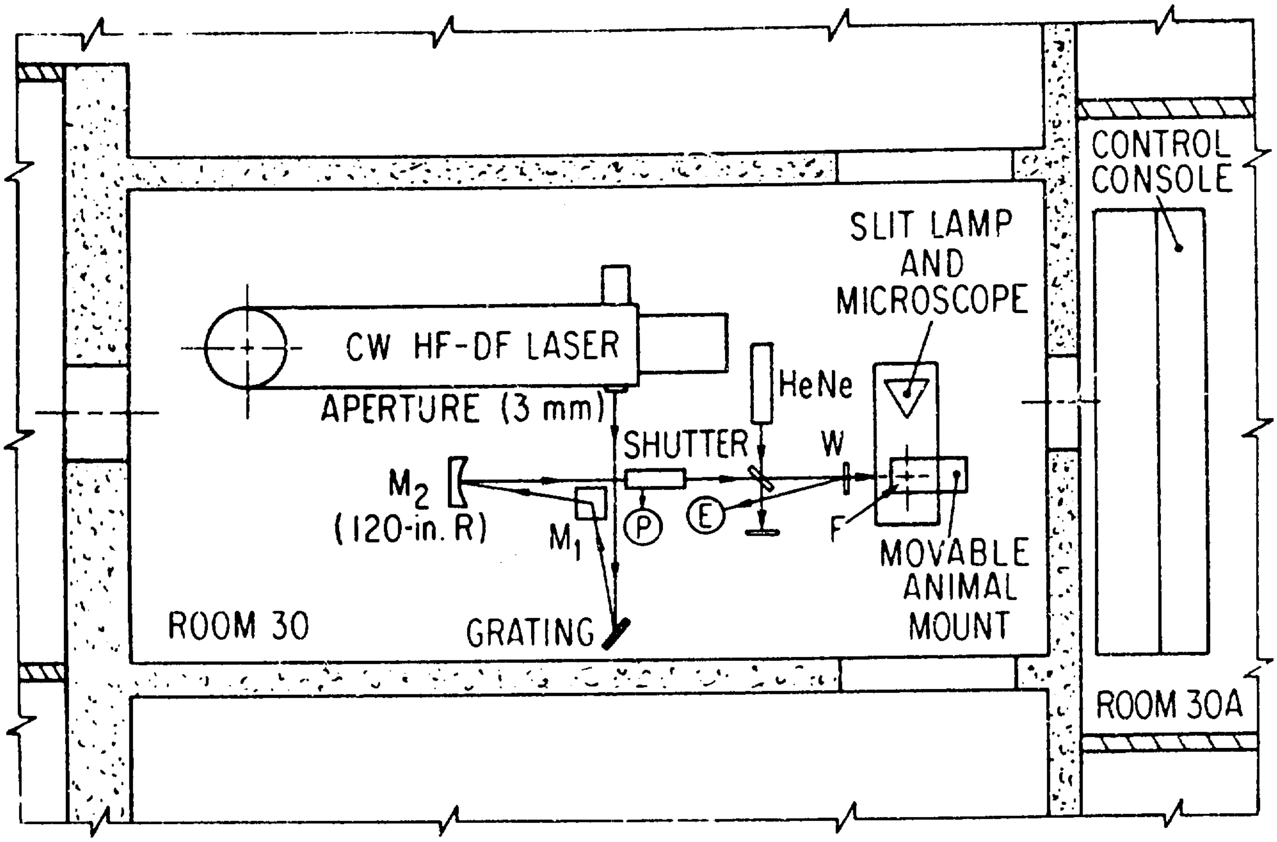

Figure 1. Ocular Damage Study Experimental Layout for CW Laser

(Distance from aperture to M_2 = 141.5 in.; distance from M_2 to F (focus) = 104.0 in.)

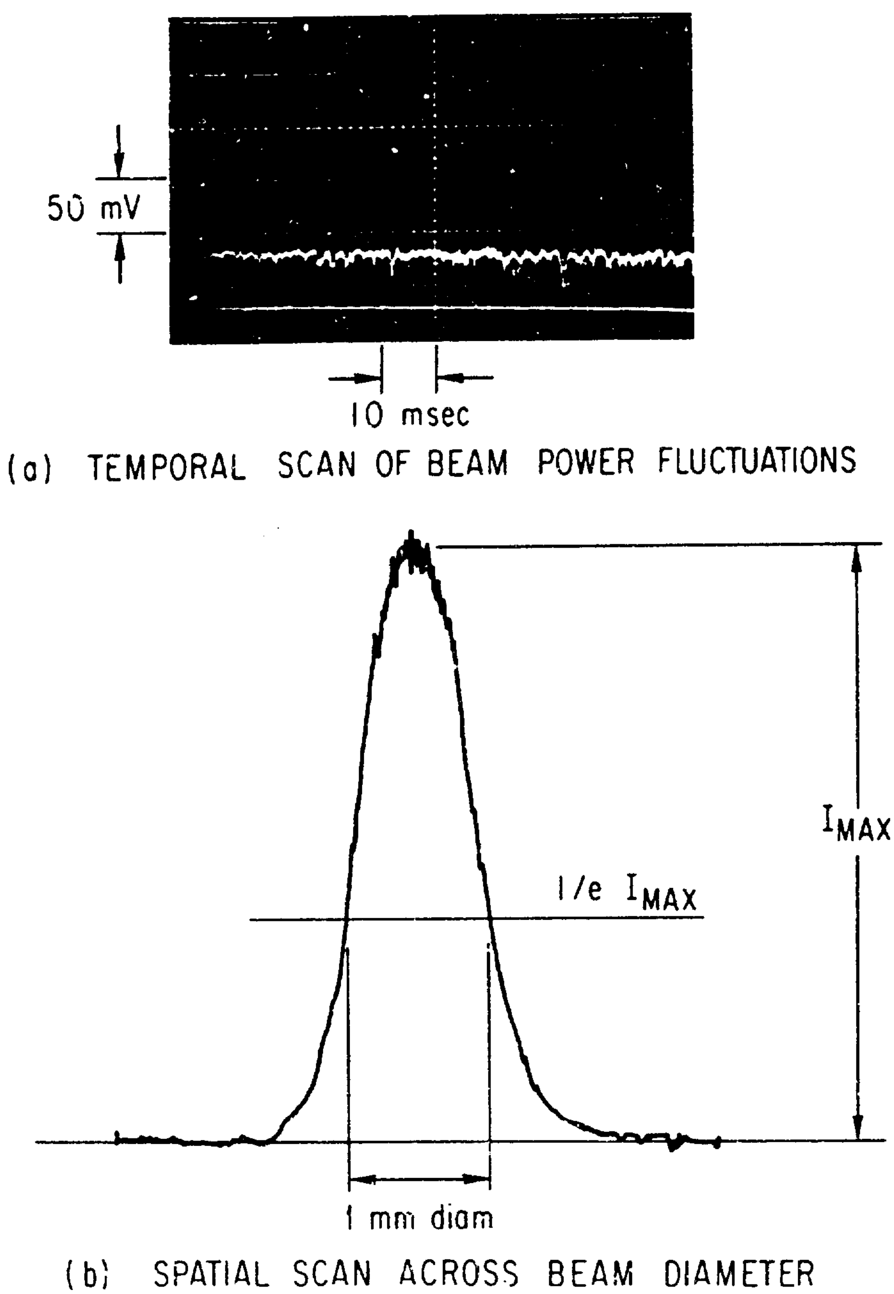

Figure 2. HF CW Laser Radiation Scans
at Beam Focus F

each test run. The actual energy delivered to the test object at the focus was monitored by a calibrated energy meter E from radiation reflected from a BaF_2 window W. A HeNe alignment laser and beam splitter were placed in the system, as shown in Figure 1, so as to provide a visible beam colinear with the IR beam for alignment at the focus prior to HF or DF laser irradiation.

The test object of these studies was the cornea of a rhesus monkey placed at the point of beam focus F. The anesthetized subject monkeys were held in a movable mount on a test stand, which also included a slit lamp (biomicroscope) for observation and photography of the corneas. The experimental array is shown in Figure 3. A monkey under observation with a biomicroscope after testing is shown in Figure 4.[1]

The pulsed pin laser used in these studies is housed in Room 360C, Building 130, Aerodynamics and Propulsion Research Laboratory.[2] Figure 5 illustrates the arrangement of the pulsed laser animal holder, slit lamp, and associated optical parts. The optics were arranged to yield a nominal 1-mm spot size (1/e point) at the focus. All exposures were for a 100-nsec duration, and no shutter was employed in these tests.

The pulsed laser was used with a multifrequency output in both HF and DF operation. Output power was controlled by means of the excitation voltage. The radiation spectra of both HF and DF laser operation were obtained for the excitation voltages of interest.

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[1]The test animals were under the care of animal specialists and were completely anesthetized when undergoing tests and maintained in accordance with the "Guide for Laboratory Animal Facilities and Care" published by the National Academy of Science - National Research Council. The experimental studies were to determine minimal damage levels, and thus the exposures were only of sufficient magnitude to induce initial lesion formation. The lesions formed in the outer epithelial tissue of the cornea immediately after exposure and appeared as small white spots < 1 mm in diameter. These lesions were in all instances completely healed within 24 hours after laser beam exposure, thus no permanent eye damage to the monkeys was sustained.

[2]Characteristics of this laser are discussed in J. S. Whittier and M. L. Lundquist, "High Brightness Pulsed HF Laser" (to be published).

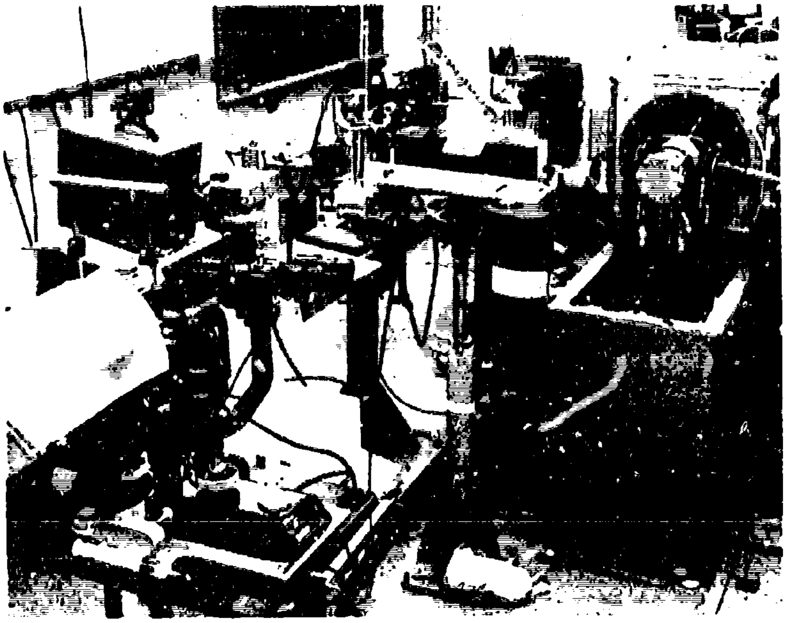

Figure 3. CW Laser Experimental Array for Ocular Damage Studies

Figure 4. Anesthetized Rhesus Monkey under Biomicroscope Observation after Laser Beam Irradiation

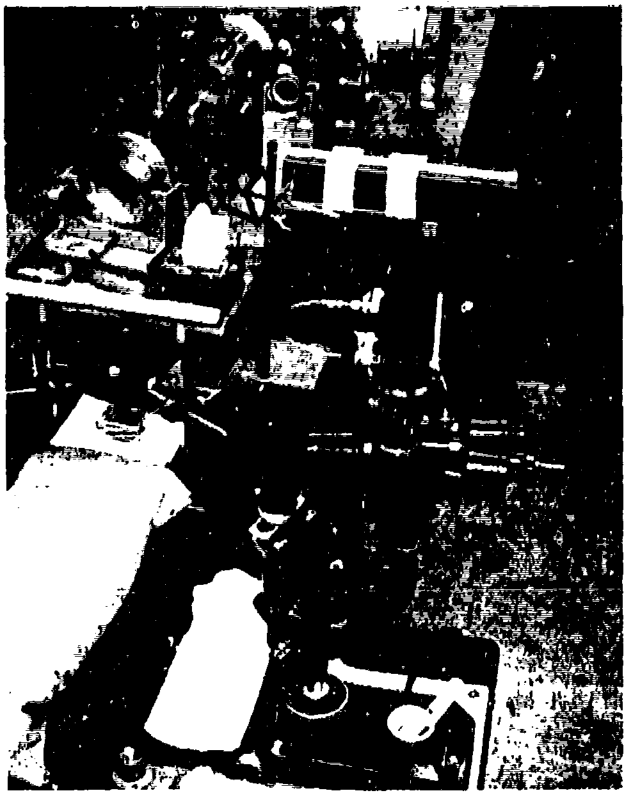

Figure 5. Pulsed Laser Experimental Array for Ocular Damage Studies

III. RESULTS AND DISCUSSION

Approximately 270 rhesus monkey eyes were irradiated by the continuous wave and pulse mode chemical lasers; each eye received at least five exposures. Because of the strong variation of the Lambert absorption coefficient in water in the 2.7- to 3.0-μm range, it was decided to obtain continuous HF data at two separate wavelengths. CW HF data were obtained for exposure times at 500, 100, and 10 msec at 2.7952 μm wavelength, $P_2(5)$ and for exposure times of 500, 100, and 25 msec for 2.7275 μm wavelength, $P_2(3)$. Power levels ranged from ~0.1 to ~1.0 W. CW data were also obtained for the DF laser without spectral separation. Spectrometric analysis showed the laser to be operating on two lines, 3.6979 μm, $P_2(5)$ and 3.7307 μm, $P_2(6)$, simultaneously. Preliminary data for exposure times of 500 and 100 msec were obtained. However, shutter difficulties precluded completion of a thorough testing program. In addition, data were obtained for the pulsed laser operating multi-frequency with both HF and DF. The half-power pulse width was 100 nsec.

The testing sequence involved exposure of corneas to several power levels bracketing the expected damage levels, so that the uncertainty in the threshold value was reduced. Thereafter, up to 100 separate exposures at power levels in the neighborhood of the nominal threshold value were made at a fixed exposure time. Determination of the presence of a lesion was made by visual observation of the cornea with a slit lamp. These data are undergoing statistical analysis at SAM. Detailed results of this study will be published by SAM at a later date. The values included in this report are nominal and are not to be construed as final or definite beyond establishing general exposure levels, trends, and relative effects at the different wavelengths studied. The nominal threshold values for lesion formation are presented in Table 1 and, according to convention, are expressed in terms of millijoules delivered uniformly over the area of a 1-mm-diam circle.

The threshold values are based on the measurement of the total energy or power in a Gaussian beam and the beam profile. For a Gaussian beam,

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Table 1. Threshold Energy for Minimal Visual Corneal Damage

			Threshold Energy, mJ [a]				
Laser	λ, μm	Designation	0.500 sec	0.100 sec	0.025 sec	0.010 sec	10^{-7} sec
CW HF	2.7952	$P_2(5)$	50	21	-	7.5	
CW HF	2.7275	$P_2(3)$	55	22	12.5	-	
Pulsed HF	Multi-line						0.82
CW DF	(3.6979) and (3.7307)	$P_2(5)$ and $P_2(6)$	150	68	-	-	
Pulsed DF	Multi-line						2.68

[a] Energy delivered uniformly over the area of a 1-mm-diam circle.

the peak flux (i.e., threshold value) corresponds to the total power in the Gaussian beam divided by the beam area at the 1/e "waist". A nominal value of 1 mm diameter was assumed for the 1/e waist diameter, although the actual measured values currently undergoing analysis may vary slightly from this value. This possibility further emphasizes the need to accept the data as preliminary only. The data are also plotted in Figure 6 as threshold energy required for minimal visual corneal damage over a 1-mm-diam circular area vs exposure time.

The general concave upward shape of the damage exposure curves is consistent with expected results. More energy is required for threshold damage to result from the long-duration pulses than from the very short-duration pulses. This is due to the increasing thermal relief provided by conduction into the surrounding tissue with increase in exposure time.

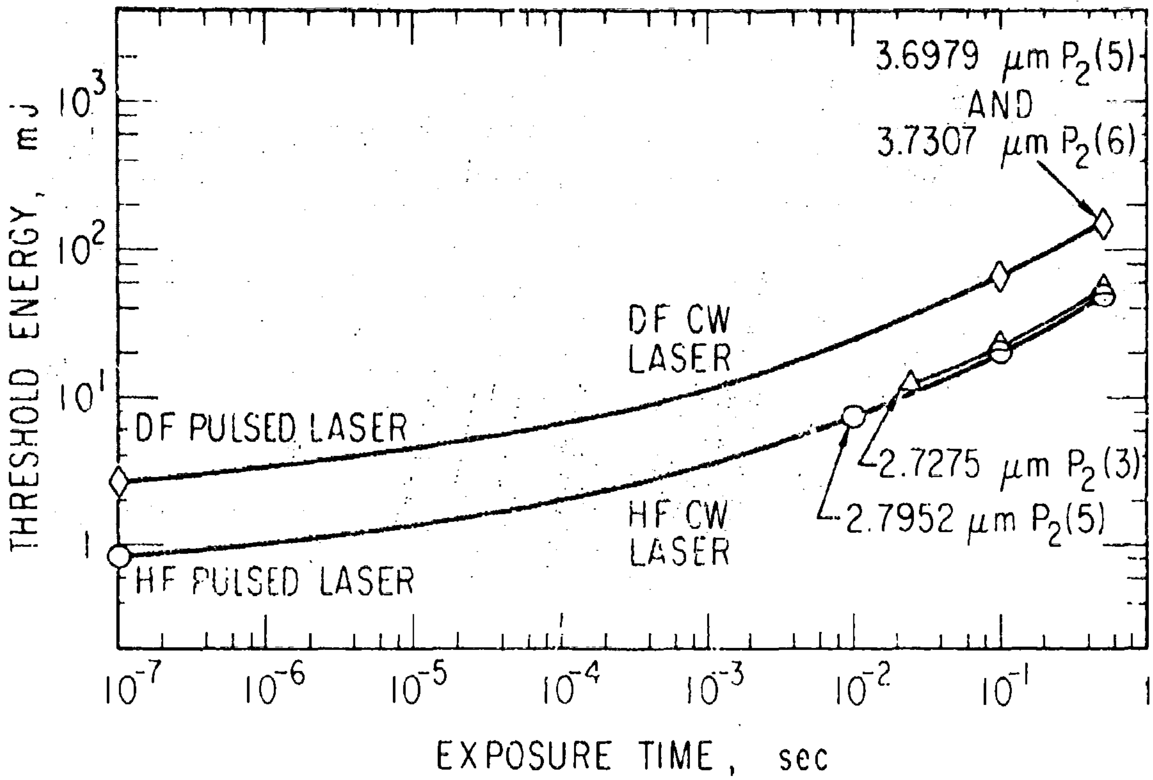

Figure 6. Damage Threshold Energy vs Exposure Time

Though the data have not undergone statistical analysis, the following general conclusions seem to be valid.

1. In the pulsed experiment, the corneal damage threshold per eye was higher for DF than for HF. This is as expected on the basis of the absorption coefficient of water in the infrared. In addition, the extent of damage was significantly different, in that more corneal pigment epithelium cells were damaged by DF than by HF. HF lesions were extremely superficial and may be classified by some eye experts as not being true ophthalmologic damage.
2. The corneal damage threshold values for the 2.795- and 2.727-μm HF wavelengths obtained from the continuous wave experiment do not seem to be significantly different. However, differences were again noted in the extent of corneal pigment epithelium damage. The lesions produced by the 2.727-μm wavelength seem to resemble those produced by CO_2 laser radiation more than those produced by the 2.795-μm wavelengths. On the basis of the absorption coefficient of water in the infrared, this is expected.
3. The corneal damage threshold values for the continuous-wave DF experiment were also higher than those from HF. Thus, the threshold energy is higher for DF (by a nominal factor of 3) than for HF laser wavelengths for exposure times from 100 nsec to seconds.

While the data span seven decades in time to the end points and appear consistent, there are nevertheless no data for five of the decades. Completion of damage curves requires additional experimental work in the unworked time domains. SAM is considering further field test efforts to obtain pulsed data from a pulsed diagnostic HF/DF laser developed in the Aerodynamics and Propulsion Research Laboratory that operates in the 10^{-5}-sec range.

A recent draft of a proposed standard on safe use of lasers is currently undergoing acceptance voting by the involved committee members. If approved, it will be submitted to the American National Standards Institute for consideration as an ANSI standard (Ref. 3). The maximum permissible exposures recommended in the draft for wavelengths from 1.4 to 13 μm are presented in Figure 7. The values are average radiances over a 1-mm-diam sampling aperture. The damage threshold values measured in these tests are also indicated in the figure. It is seen that the recommended standard is conservative. The HF threshold values lie ~1 order of magnitude higher than the

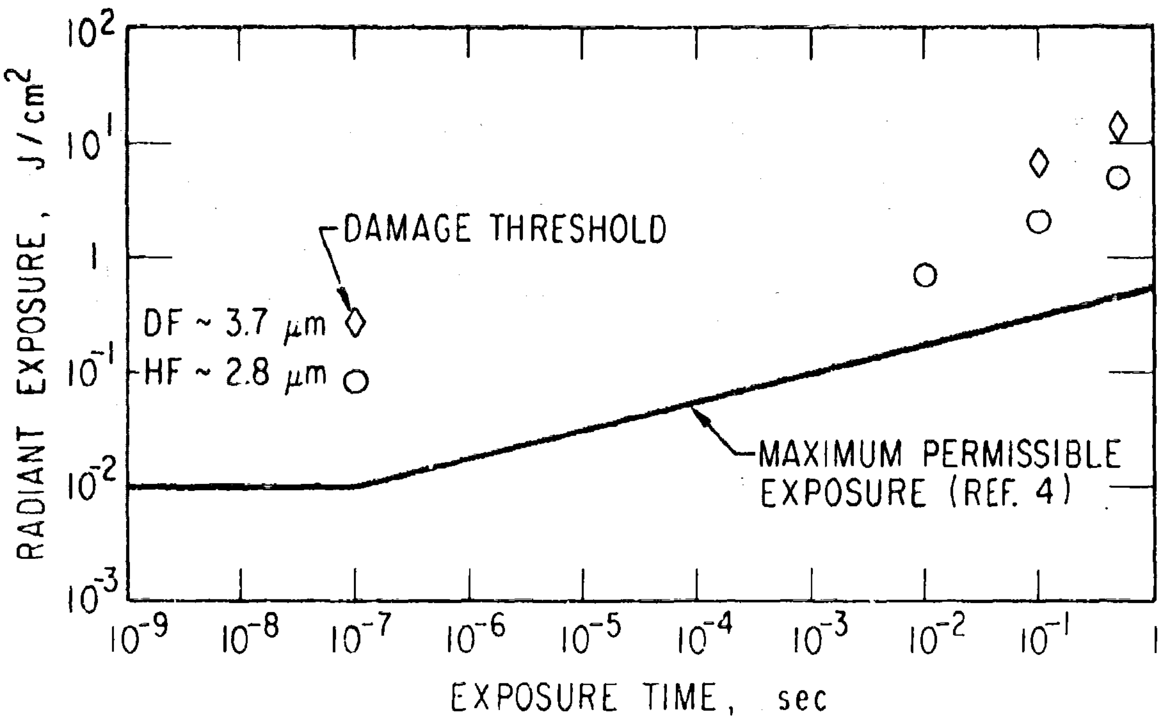

Figure 7. Damage Threshold and Maximum Permissible Exposure

recommended maximum permissible exposure levels. The DF values lie nominally a factor of 30 higher. These are the first experimental values obtained in the region between 1.54 μm (Erbium laser) and 10.6 μm (CO_2 laser) and constitute a necessary confirmation of the conservative nature of the exposure estimates for the ~2- to 4-μm wavelength portion of the spectrum.

IV. CONCLUDING REMARKS

The test series described herein resulted in the first laser threshold damage data in the wavelength region from 2 to 4 μm and is a significant contribution in establishing safety criteria for Air Force-operated laser systems.

Further field tests are under consideration by the School of Aerospace Medicine at The Aerospace Corporation for the purpose of obtaining biomedical safety criteria data from single-pulsed (10 μsec) HF/DF, multi-pulsed HF/DF, continuous DF, pulsed CO, and picosecond, mode-locked neodymium laser systems.

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1. H. Mirels and D. J. Spencer, "Power and Efficiency of a Continuous HF Chemical Laser," IEEE Quantum Elect. QE-7, 501 (1971).

2. D. J. Spencer, H. Mirels, and D. A. Durran, "Performance of CW HF Chemical Laser with N_2 or He Diluent," J. Appl. Phys. 43, 1151 (1972).

3. "ANSI Panel Voting on a Proposed Safety Standard," Laser Focus 8, 22 (1972).

APPENDIX. ARC HEATER OPERATING CONDITIONS AND LASER CAVITY CONFIGURATION

He mass flow – 5 g/sec

SF_6 mass flow ≤ 2 g/sec (varied for power control)

H_2 mass flow = 0.16 g/sec

D_2 mass flow ≤ 0.35 g/sec (varied for power control)

O_2 mass flow = 0.8 g/sec

Arc Voltage = 200 V

Arc Current = 300 A

Plenum Pressure = 16 psia

Cavity Pressure = 4 Torr

Far Mirror: 120-in. radius concave

Coupling Mirror: Silicon flat with 3-mm aperture

Mirror Separation: 27 in.

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